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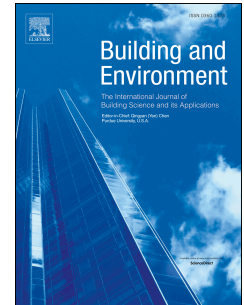
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# Accepted Manuscript

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## Methods to determine whole building hygrothermal performance of Hemp-lime buildings

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### Highlights

- Aggregated set of hygrothermal material properties for hemp-lime
- Effect of discretization on component level moisture buffering
- Whole building hygrothermal performance with EnergyPlus and IES
- Effective moisture capacitance model to represent relative humidity buffering
- Moisture admittance approach with resistance and capacitance to determine zone moisture buffering

### ABSTRACT

Hemp-lime is a potentially useful building material with relatively low embodied energy and moderate-to-good thermal performance, coupled with good moisture buffering capacity. However, some uncertainty remains with regards to its in-situ thermal performance and the capability of building energy simulation tools to accurately predict envelope performance and subsequent energy demand of buildings constructed of such vapour-active materials. In this paper we investigate the hygrothermal performance of buildings with walls constructed from hemp-lime. Component-level moisture buffering simulation employing the EnergyPlus simulation tool is found to be within 18% of Wufi Pro analysis and laboratory measurements. The coarseness of component discretization is shown to effect moisture buffering leading to the observation that finer discretization should be employed to improve EnergyPlus HAMT model accuracy. Whole building simulation of the BESTEST building with hemp-lime components indicates that moisture transport inclusion has a large influence on zone relative humidity but little influence on overall heating and cooling demand. A simple effective-capacitance model is able to represent humidity buffering but is less good at representing the response to sudden moisture loading. An additional resistance parameter is added to the model and an IES-ve simulation using this approach is shown to give a close match to the full hygric simulation.

### Keywords

Hemp-lime, Hygrothermal analysis, Effective moisture capacitance model, IES simulation.

## 1. Introduction

The use of natural fibre materials, such as hemp-lime, hemp-fibre, flax, straw etc., as building elements e.g. external walls, internal partitions etc. combines the benefits of renewable low carbon materials with hygric and thermal performance. Hemp-lime has many benefits compared to conventional building materials and a number of these were outlined by Shea et al. [1] as follows:

- Potentially useful hygrothermal performance,
- Sequestration of atmospheric CO<sub>2</sub>,
- Hemp shiv is more resistant to biological decay than some other bio-based building materials (e.g. straw),
- Hemp cultivation requires lower levels of fertilisation and irrigation than other crops,
- The hemp plant grows very rapidly, to heights of up to 4 m within 4 months, which gives it the potential to act as a 'break crop', allowing optimisation of yields of the primary crop.

Indoor humidity is important to comfort and health and the durability of construction materials. Indoor humidity affects respiratory comfort, skin humidity and perceived indoor air quality (IAQ) [2, 3]. Since perceived IAQ is closely linked to humidity, the moisture buffering of the building fabric has potential for reduced energy use through reduction of the required ventilation rate [4]. Humidity and mould growth also have significant implications for occupant health [5]. These issues are particularly important for natural fibre materials as they tend to have higher vapour permeability than conventional building materials. One barrier to the more widespread use of hygrothermal simulation is the shortage of complete sets of hygroscopic material property data particularly for natural fibre materials.

The high vapour permeability of such materials can be useful but hygroscopically complex behaviour also presents challenges in describing the thermal performance of the materials, which then affects any subsequent whole building performance analysis of any development containing such materials. Whilst a number of tools such as Wufi, EnergyPlus and ESP-r have successfully integrated heat and moisture transport models, there are still a number of barriers to their widespread use, not least where material property data are scarce. Kramer et al. [6], in their systematic review of simplified thermal and hygric models, highlight the need for simplified 'white box' hygric and thermal building model with physical meaning. Wufi, EnergyPlus and ESP-r use numerical approaches as outlined by Künzle [7] to simulate combined heat and moisture in construction components. Annex 41 studied a number of software tools for whole building hygric performance simulation [8], which included inter-model comparison [9]. An alternative, and simpler, option for the simulation of humidity buffering in whole building models employs the use of an effective capacitance model. Such models attenuate moisture when it is introduced into the zone by multiplying the air volume into which the moisture is mixed. These simplified models have benefits over complex models such as ease of use, speed of calculation, and, in the case of effective capacitance models, the parameters have real physical meaning [10], which aids interpretation and understanding.

In the following section we present the hygric and thermal material properties of hemp-lime and in Section 3 the accuracy of different modelling approaches is investigated by inter-model comparison and comparison with laboratory measurements. The HAMT model in EnergyPlus is compared with laboratory results and Wufi Pro component level results in terms of component moisture buffering.

In Section 4 the HAMT model is then used to investigate the sensitivity of whole building performance to moisture transport in hemp-lime building components. Building simulation tools that incorporate moisture transport are not always widely used in practice. For example, in the UK the most widely used simulation tool is IES, which does not currently calculate moisture transport. For this reason, the performance of the zone effective capacitance model is investigated in this paper, as it is an approximate model that could readily be incorporated into this popular simulation tool. The capacitance concept is applied in IES with the addition of a connecting air network adding a resistance parameter.

## 2. Hemp-lime hygrothermal material parameters

Hemp-lime can be produced at different densities, depending on its use, and typically ranges from 200 to 500 kg/m<sup>3</sup>. Density has a significant effect on the hygrothermal properties of hemp-lime, although other factors may have an influence, such as the types of lime and hemp used; the ratio of lime, hemp and water when mixed; the sample age, and, therefore, the extent of carbonation of the lime.

Most of the characterisation of hemp-lime has been conducted in France and Belgium, where there is a tendency to use a more dense mix for walls compared to the UK. Lower density has been favoured in the UK as it results in a lower thermal conductivity, therefore achieving compliance with building regulations without the need to make excessively thick walls. There is little published experimental data for lower density hemp-lime (less than approx. 300 kg/m<sup>3</sup>) and consequently experiments are currently underway which will determine the key hygrothermal properties for lower density hemp-lime composites. To make prior estimates, the results of previous studies have been used to extrapolate some key values. The parameters used in the simulations presented in this paper are a mixture of experimental and estimated values.

The following parameters are required for combined heat and moisture simulation:

- Bulk density,
- Porosity,
- Specific heat capacity,
- Moisture-dependant thermal conductivity,
- Moisture storage function,
- Liquid transport coefficient for suction,
- Liquid transport coefficient for redistribution,
- Water vapour diffusion resistance factor.

### 2.1. Methods to gain model parameters

Porosity was estimated via linear extrapolation when plotted against density using data from Cerezo [11], Collet [12] and Collet et al. [13]. In these studies porosity varied between 72% for a 460 kg/m<sup>3</sup> sample to 80% for 256 kg/m<sup>3</sup>. The specific heat capacity was similarly estimated using Evrard [14], Evrard & De Herde [15] and Tran Le et al. [16], which gave values between 1000 J/kgK and 1560 J/kgK. The material data is summarised in Table 1.

Experiments have been conducted in accordance with ISO 12572 [17] to determine the water vapour diffusion resistance factor ( $\mu$ ), whereby a relative humidity gradient is created across the sample so the resulting difference in partial vapour pressure creates a vapour flux. The rate of water vapour diffusion is measured gravimetrically and used to calculate  $\mu$ . The rate varies depending on the humidity gradient chosen, particularly at high humidity when liquid water forms in the pores so that liquid

transport takes over from diffusion. Collet et al. [12] produced equations for curves fitted to experimental data for samples of hemp-lime measured at different humidity gradients. These equations were used in combination with experimental data to estimate a full set of values presented in Table 2. This data is used as input for the simulation that produced the results presented later.

Table 1 Material parameters for hemp-lime.

<i>Material parameter</i>	<i>Parameter value</i>
<i>Bulk Density (kg/m<sup>3</sup>)</i>	304
<i>Porosity (-)</i>	0.8
<i>Specific heat capacity (J/kgK)</i>	1270

Table 2 Water vapour diffusion resistance function for hemp-lime.

<i>Relative Humidity fraction (-)</i>	<i>Water vapour diffusion resistance factor, <math>\mu</math>, (-)</i>
0	6.58
0.3	6.58
0.4	6.53
0.5	6.28
0.6	5.38
0.7	3.62
0.8	1.88
0.9	0.85
1	0.46

The thermal conductivity ( $\lambda$ ) of a conditioned hemp-lime sample was measured using a Fox 600 heat flow meter (HFM) as described in Holcroft & Shea [18], whereby a temperature gradient is created across the sample and the heat flux measured once it has reached steady-state, which is then used to calculate  $\lambda$ . There are however potential inaccuracies in this technique as it takes much longer for the sample to reach hygric than thermal equilibrium, although subsequent tests at smaller temperature gradients, and for a range of sample moisture contents, provide confidence in the accuracy of the results presented here.

The thermal conductivity was assumed to increase linearly as the moisture content increased as shown in Evrard & De Herde [15]. The same gradient of increase was assumed but aligned with the value measured using the HFM and presented in Table 3. The values produced by Evrard & De Herde for the moisture storage function (sorption isotherm) were also used in the simulation and this is presented in Table 4. The same paper was the source of the liquid storage functions presented in Table 5 and Table 6.

Table 3 Moisture dependant thermal conductivity of hemp-lime.

<i>Moisture content (kg/m<sup>3</sup>)</i>	<i>Thermal conductivity (<math>\lambda_w</math>) (W/mK)</i>
0	0.072
546	0.102

Table 4 Moisture storage function of hemp-lime.

<i>Relative Humidity fraction (-)</i>	<i>Moisture content (kg/m<sup>3</sup>)</i>
0	0
0.8	33
0.96	60
0.98	100
0.99	117
1	546

Table 5 Hemp-lime liquid transport coefficient for suction.

<i>Moisture content (kg/m<sup>3</sup>)</i>	<i>Liquid transport coefficient for suction (m<sup>2</sup>/s)</i>
0	0
28	8.00E-11
63	4.00E-09
458	8.00E-09
546	8.00E-08

Table 6 Hemp-lime liquid transport coefficient for redistribution.

<i>Moisture Content (kg/m<sup>3</sup>)</i>	<i>Liquid transport coefficient for redistribution (m<sup>2</sup>/s)</i>
0	0
28	8.00E-11
101	6.00E-10
219	3.00E-09
297	6.00E-10



### 3. Component level moisture buffering

Laboratory measurements were compared with simulation results of moisture buffering for a sample of hemp-lime. Two simulation tools were used, Wufi Pro and the EnergyPlus HAMT model.

#### 3.1. Laboratory moisture buffer test method

The moisture buffer measurements were conducted according to ISO 24353 [19]. For this method, a 200 x 200 mm sample is exposed to step changes between 53% and 75% relative humidity every 12 hours. This was repeated until the mass change during the sorption and desorption stage reached a steady state. The change in mass is the moisture buffering capacity of the material. The test sample was sealed with impermeable aluminium foil over all surfaces except one 200 x 200 mm surface. More details of these measurements can be found in [20]. The humidity cycles and isothermal conditions were produced in a climate chamber presented in Figure 1. The chamber air circulation fan was screened by a plastic mesh to minimise the effects of air movement in the chamber. Relative Humidity (RH) indicated by the chamber was referenced to a second capacitive relative humidity sensor measurement taken during the test and that sensor has an accuracy  $\pm 3.0\%$  RH at  $25^\circ\text{C}$  in the RH range of 0 to 95%, and was calibrated prior to the test using salt solutions.



Figure 1. Climate chamber laboratory set-up [20]

#### 3.2. Component moisture buffering simulation methods

The test set-up was replicated in the simulation tools Wufi Pro and EnergyPlus, in order to compare the simulation results with laboratory measurements. This involved editing weather files so that the isothermal conditions and humidity cycles matched the moisture buffering test conditions. The aluminium foil layer was added to the opposite side as that exposed to the humidity cycles. The surface resistances were matched for both simulation tools using a surface heat transfer coefficient of  $23 \text{ W/m}^2\text{K}$ . A vapour transfer coefficient of  $1.15 \times 10^{-7} \text{ kg/Pa}\cdot\text{s}\cdot\text{m}^2$  was used for the



exposed surface. This follows the approach given in the Wufi documentation for vapour transfer coefficients.

Wufi is well suited to such a component-level test with the results for moisture content in the hemp-lime layer used to show the buffering once equilibrium was reached.

Although EnergyPlus is a whole-building simulation tool, the results for a single surface were the focus of the first set of results. This gave the moisture buffering performance of a single component and was comparable to the Wufi Pro simulation and the laboratory results; and also provides a way of isolating the moisture transport performance of EnergyPlus's HAMT model. A simple cube was modelled with one surface made of hemp-lime with hygrothermal material properties and a layer of aluminium foil on the inside. The moisture content results for this surface alone are used to give the moisture buffering change in mass. These results are used to give an indication of the accuracy of moisture buffering before the HAMT model is used to simulate whole-building performance.

### 3.3. Component results and discussion

Figure 2 compares the simulated results from EnergyPlus and Wufi Pro with the laboratory results. Overall, it can be seen that the normal Wufi Pro results, with 60 elements (Wufi 60El.) have a better fit to the laboratory results than the EnergyPlus results, which are 18% greater at the peak. This is a significant difference but consistent with the variation seen in the inter-model comparison from Annex 41 [8]. The underlying approach to hygrothermal performance is similar so the possibility that discretization may be a factor for the 18% difference was investigated. The HAMT model surface was discretized with 14 elements. The normal Wufi simulation was conducted with 60 elements making up the surface.

It is considered that the Wufi 60El results are effectively grid independent as increasing the resolution to 100 elements changes the peak results by less than 1%. To illustrate how discretization resolution differences between EnergyPlus and Wufi Pro could be a factor in the peak buffering value discrepancy, coarser resolutions were introduced into the Wufi Pro model. These are presented in Figure 2 and it can be seen that the peak buffer value increases with coarser elements. This suggests that the increased peak in the EnergyPlus result is at least partly due to the coarser discretization.

Although beyond the scope of this paper, edits to the EnergyPlus source code could be made to increase the resolution. This would also greatly increase the computational resources required to run a whole building model.

Another issue is the difference in curve shape between EnergyPlus, and Wufi Pro. EnergyPlus maintains a steadier curve gradient compared to the Wufi Pro results. Wufi fits the laboratory results better for the absorption phase of the cycle. In the desorption phase of the cycle EnergyPlus gives a closer fit in terms of the curve shape. To illustrate this, the EnergyPlus moisture buffering curve was scaled so that the peak matched the laboratory results; this is shown by the EP scaled results in Figure 3.

Absorption/desorption hysteresis is an issue for moisture storage function calculation but neither program deals with this directly and a single moisture storage function was used for both simulations.

Although differences between EnergyPlus and laboratory measurements have been highlighted, this paper focuses on broad, whole building, sensitivity to hygrothermal

performance and approximate methods that can be used with industry standard tools and so the HAMT moisture transport is considered appropriate for this task.

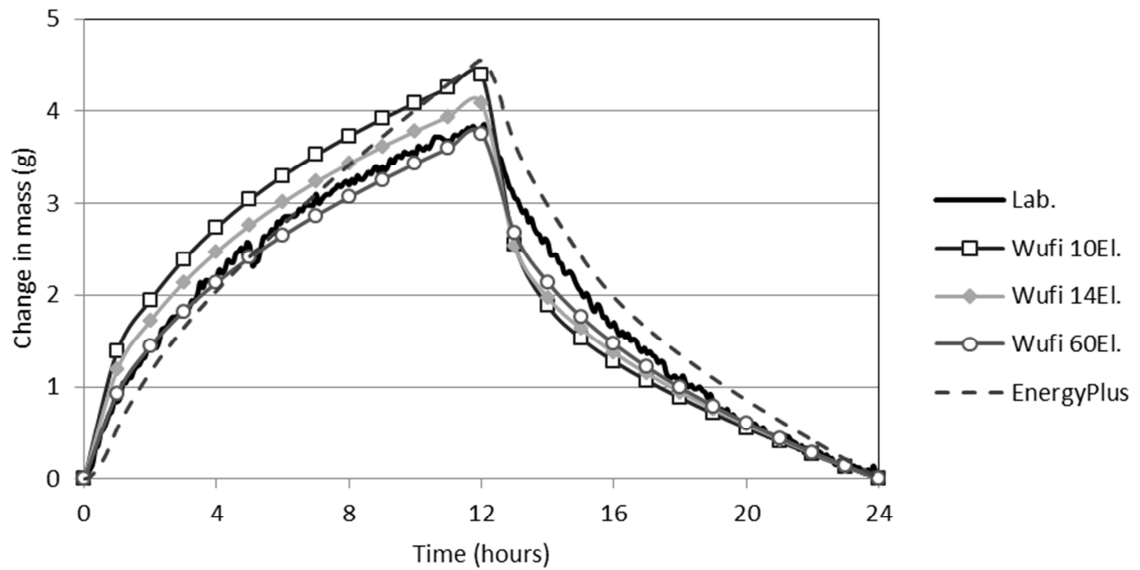


Figure 2. Moisture buffering change in mass for laboratory results (Lab.) alongside simulation results with different levels of discretization. EnergyPlus has 14 Elements, Wufi discretization is indicated in the legend.

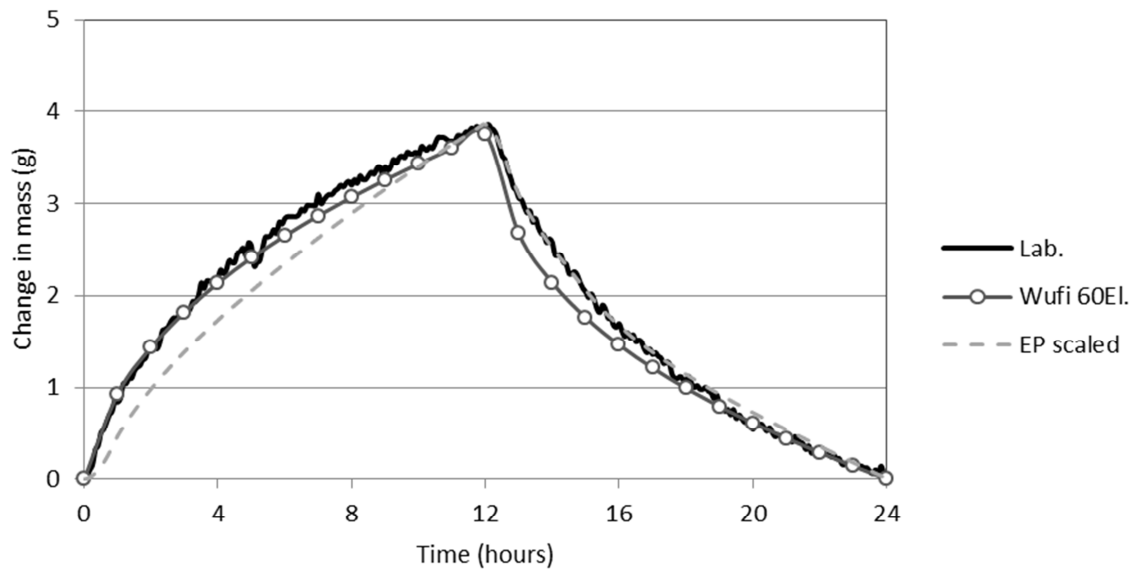


Figure 3. Moisture buffering with the EnergyPlus scaled results (EP scaled).

#### 4. Whole building performance

This section investigates whole building performance of a hemp-lime building. This illustrates how the hygric material properties affect the internal conditions that occupants would be exposed to and the energy use of the building.

The hemp-lime material properties were applied to the walls of the BESTEST building [21] presented in Figure 4. The building was modelled with a steady air

exchange rate of 0.5 ACH and a humidity burst of 500 g/h during occupied hours (08:00 – 17:00).

The walls of the BESTEST building were modelled as 200 mm of hemp-lime with and without humidity transport modelled with the HAMT model. The hemp-lime had an initial water content of 0.09 kg/kg, although it should be noted that, similarly to the laboratory testing, the output presented from all simulations follows an initial pre-conditioning period to ensure that dynamic equilibrium was reached. When simulating without the use of the HAMT model no moisture transport is included and the standard dry state material properties, shown in Table 1, are utilised alone. These results are described as “closed” with the wall constructions effectively closed to moisture. The results described as “hygric” use the HAMT model and the full set of hygrothermal material properties are used to simulate combined heat and moisture transport. All other materials are the same as the BESTEST 600 standard model [21].

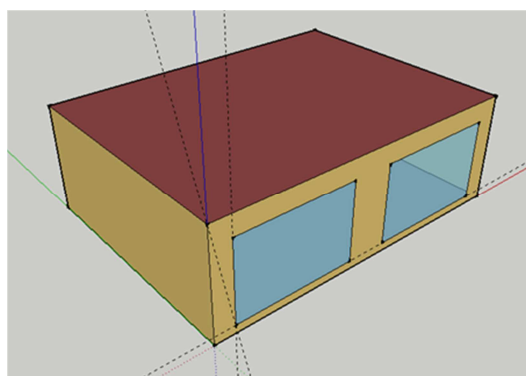


Figure 4. BESTEST building used for whole building results

The effect of moisture buffering on whole building relative humidity is presented in Figure 5. This result was with isothermal conditions from a steady condition weather file with fixed external air temperature of 23°C and relative humidity of 20%. Given these steady external conditions it is evident that the introduced bursts of humidity during occupied hours were, therefore, the cause of the relative humidity increase. The average result remains similar for both closed and hygric cases, with the hygric case averaging just over 1% RH higher than the closed results. The difference in buffering performance between the two cases is more pronounced as the hygric case only fluctuated by 17% RH whilst the closed case varied by more than double at 36%. The closed model indicates an RH range of 24 – 60% whilst the hygric model presents much a lower swing in RH from 30 - 47%. With no moisture buffering capacity from the building fabric, the closed model responds quickly to the moisture burst and then to the 0.5 ACH of external air at 20% RH. Conversely the material moisture buffering of the hygric case provides attenuation of the peaks resulting in more stable internal conditions, which has implications for occupant health, due to reduced risk of mould growth on surfaces, and occupant comfort, as a result of reduced diurnal variation, as well as improved energy performance due to reduced need for humidification or dehumidification of the occupied space.

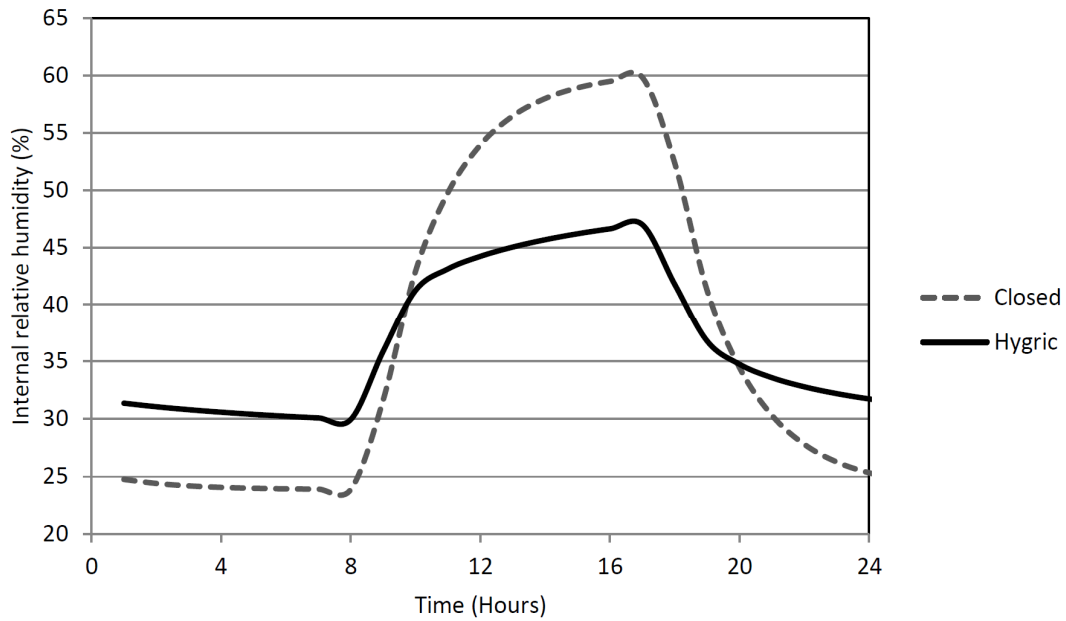


Figure 5. Whole building internal relative humidity

To investigate the impact of moisture buffering on building peak heating and cooling loads and annual energy use the closed and hygric models were run with London Gatwick IWEA weather data. Peak loads are presented in Figure 6 and total yearly energy demand is presented in Figure 7.

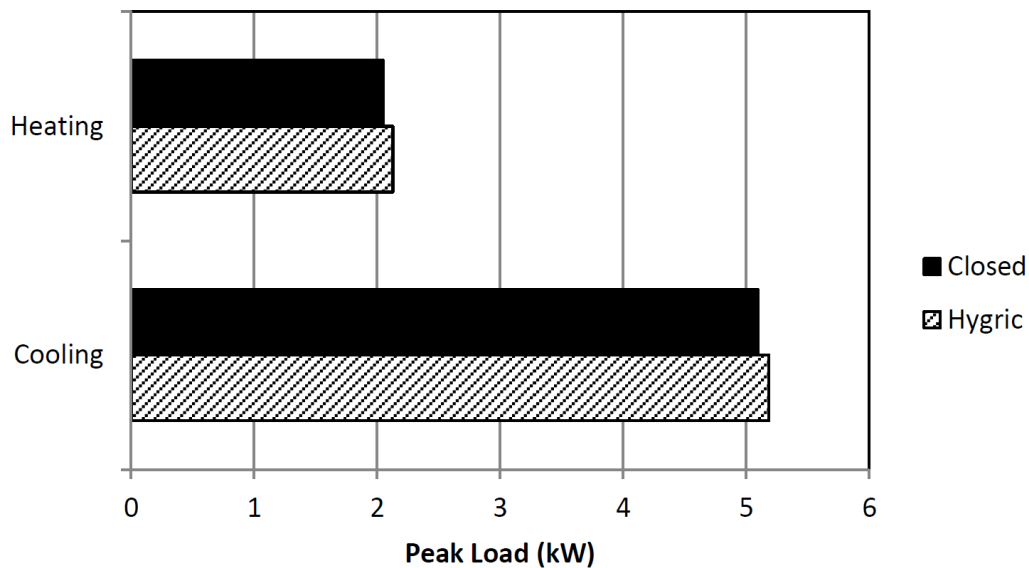


Figure 6. Peak loads for a Gatwick weather year

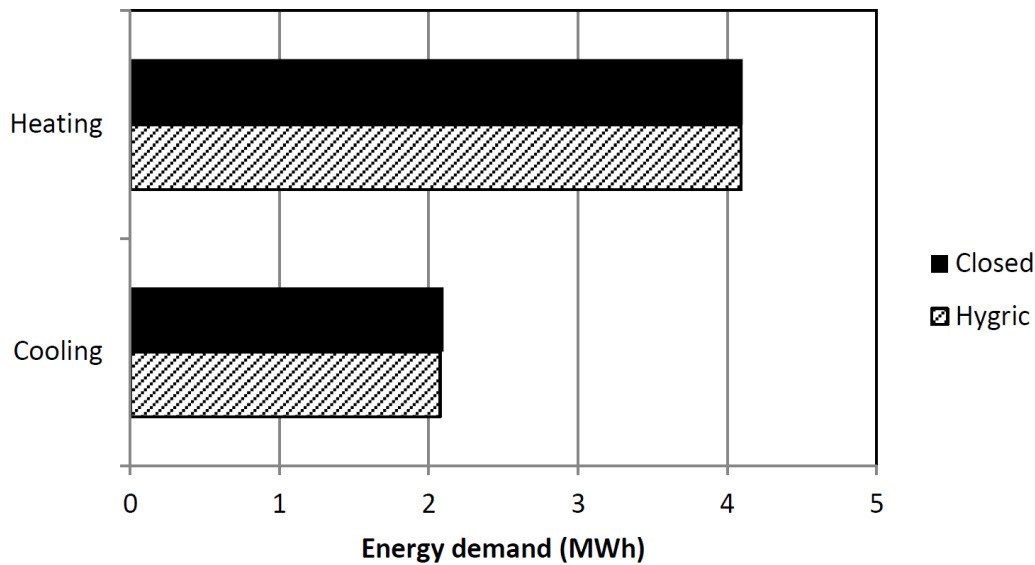


Figure 7 Energy demand for a Gatwick weather year

The heating and cooling set-points were set, as prescribed in the BESTEST building [9], to 20°C and 27°C respectively. Accordingly, at any period in the 24-hour day if the space air temperature falls below 20°C heating is demanded and, similarly, if internal air temperature rises to 27°C cooling is enabled. Sensitivity of heating and cooling is relatively low for the BESTEST building with a 1.6% increase in peak cooling loads and a 3.8% increase in peak heating loads when a full hygric simulation is used for the hemp-lime walls. The slightly higher peak load for heating in the hygric case is likely due to the increased, moisture dependent, thermal conductivity of the hemp-lime wall material properties (Table 3). In terms of overall energy demand for the full year the difference due to adopting the full hygric simulation is even smaller with a 1.1% decrease in yearly energy demand for cooling and a 0.3% decrease in yearly heating energy demand, compared with the closed case. These are small changes compared to those seen in the internal relative humidity which corresponds to other simulation studies using the BESTEST building [9]. The dynamic response of the building fabric and that interaction with intermittent occupation by the building users will clearly impact both peak loads and annual energy use due to heating and cooling. Additionally, there may be other energy savings related to relative humidity buffering that are not represented in the BESTEST model, for example, a reduction in fan use in bathrooms and also associated reductions in heating demand from reducing the need for ventilation to ameliorate the internal environment following bursts of excess moisture. The results given in Figure 6 and Figure 7 are for the BESTEST case, with a UK (Gatwick) weather file, and buildings that are less closely controlled or subject to different climatic conditions may well perform differently. The BESTEST building was subsequently converted to a free-running 'passive' condition (no heating or cooling) and orientated so the glazed surface faced north to reduce the contribution to overheating from solar gains. Hours over 28°C are presented in Figure 8 to indicate the level of overheating.

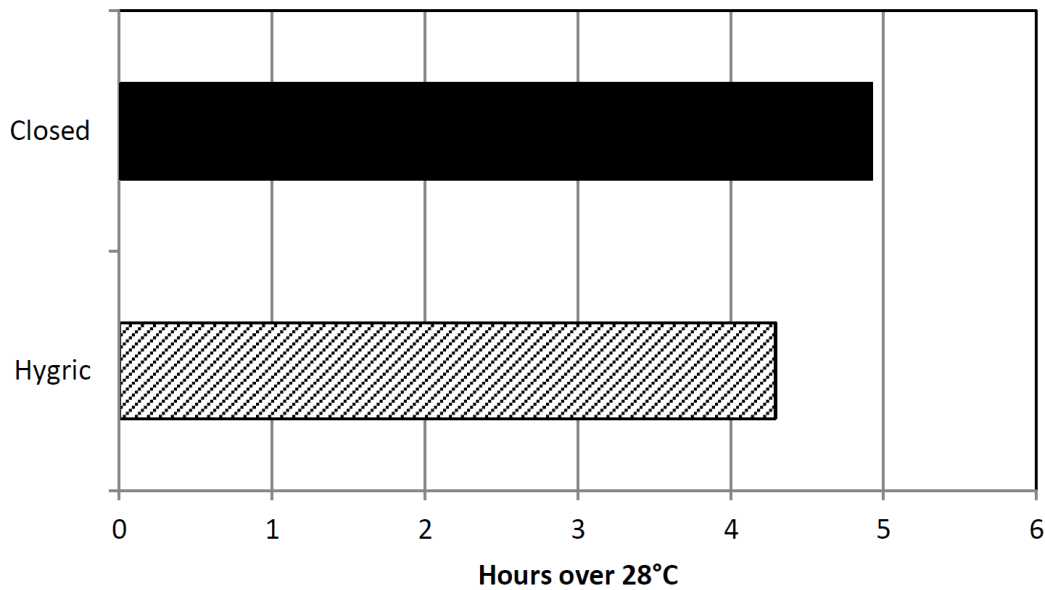


Figure 8 Overheating levels for the north facing BESTEST building.

It can be seen from Figure 8 that even with the glazing oriented north the hours over 28°C are above 1% and the building would be classified as overheating according to CIBSE Guide A [22]. The levels of overheating do change when using the hygic simulation in contrast to the closed materials. The change is relatively minor though with 0.6% more hours over 28°C for the closed model compared to the hygic model. This could be important for a building very close to the 1% limit. In general, though these results suggest that the use of full hygic simulation is mainly a priority if health and comfort is a primary concern or if knowledge of the moisture content of the construction is required to evaluate durability.

### 5. Effective capacitance model

This section investigates the use of effective capacitance models as a simplified way of simulating moisture buffering of the hemp-lime BESTEST building. The effective capacitance approach adds additional air volume to the zone; this effectively dilutes any moisture changes. The effective capacitance approach is numerically considerably simpler than the full hygic simulation, which requires more computational resources. The buffering of all elements is lumped together so the addition of hygic elements would be simple. As well as the effect of hygic building materials, the buffering effect of furniture etc. can be approximated and added to the zone capacitance. This approach only aims to represent humidity buffering, and the effects of water content on material thermal properties or the distribution of moisture in materials is not calculated. The first approach was to use the EnergyPlus Zone Capacitance Multiplier object [23] in the BESTEST building modelled with an isothermal weather file. Three cases are displayed in Figure 9.

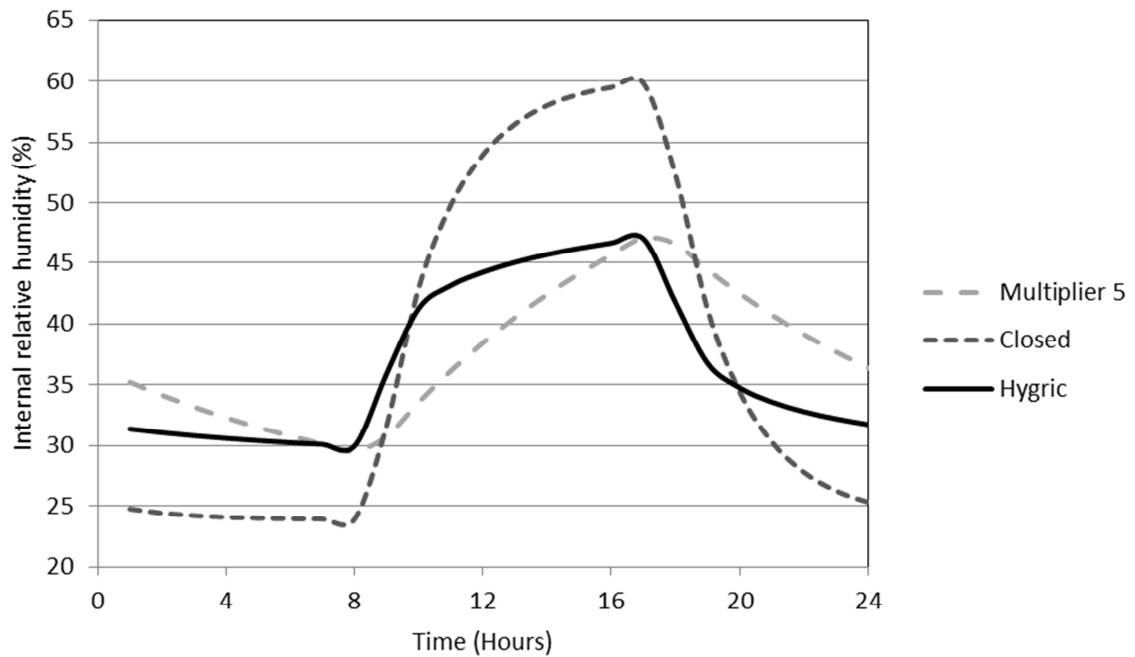


Figure 9. Comparing models for whole building moisture buffering for EnergyPlus.

As previously, “Hygic” indicates walls that are hygrically open using the HAMT model to represent moisture transport. “Closed” means the surfaces do not have moisture transport and no zone multiplier is applied to the air volume. “Multiplier 5” refers to surfaces that do not have moisture transport but the air volume is multiplied by 5.

A multiplier of 5 was chosen so that the peak result matched the hygic case. To use this approach more widely a method for selecting the capacitance multiplier value in a systematic way would need to be developed. One possibility would be to use moisture buffering material results and exposed surface areas.

As can be seen in Figure 9 when an appropriate multiplier is used the magnitudes of the peaks and troughs and average humidity are more closely approximated for this case. The dynamic response to a sudden change in moisture load is not so well represented; this can be seen in the difference in the shape of the curve. The internal relative humidity with a capacitance multiplier of 5 could still be seen as an improvement on the results of the closed model.

### 5.1. Resistance-capacitance model

Using EnergyPlus’s Zone Capacitance Multiplier object means the zone air has instant access to the extra capacitance and there is no resistance to moisture flow. In reality, the hygic materials take time to absorb and release moisture. This is why the curve shape for the capacitance model is different in Figure 9. Using additional capacitance zones connected by HVAC equipment to the physical zones also introduces the ability to control the access to the extra humidity capacity by controlling the speed of the connecting fan. Such an approach can be described as a resistance-capacitance model. For the next results, an effective capacitance resistance approach was implemented in the widely used software, IES, which currently does not support moisture transport. This was done by adding an additional capacity zone and setting up a HVAC system to circulate air between the capacity zone and the physical



simulated zone. Figure 10 presents a representation of this IES effective capacitance model.

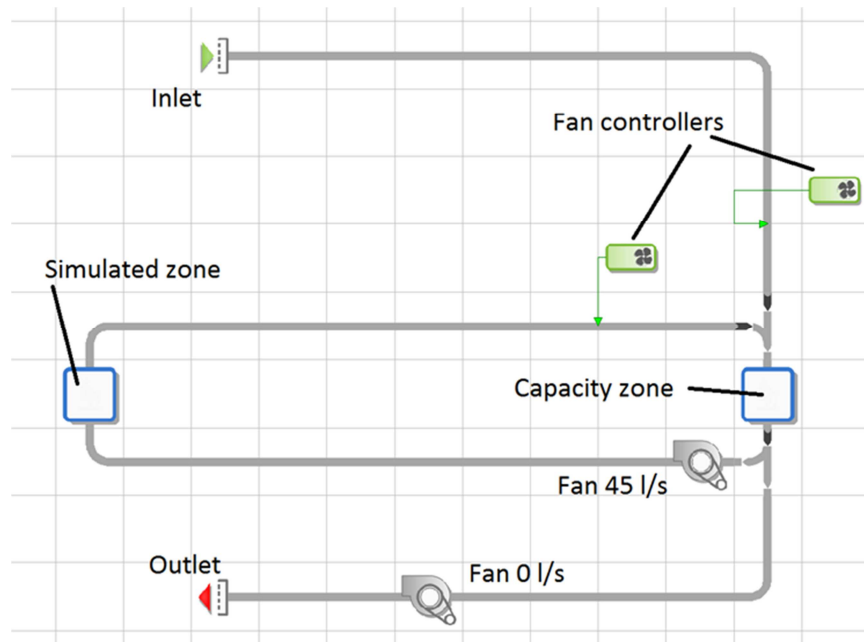


Figure 10. Representation of the effective capacity model implemented in IES (IES ECM)

The IES ECM is a simple air loop connecting the simulated zone with the moisture capacity zone. The inlet and outlet are included to satisfy IES ApacheHVAC internal checks but the fan in this part of the system is set to zero flow so the circulation of air between the BESTEST simulated zone and the capacity zone is the only one that occurs. The IES ECM has a fan flow rate of 45 l/s which connects the BESTEST building zone with a capacity zone 5 times the volume of the BESTEST simulated zone. The results of this model are illustrated as “IES ECM” in Figure 11 where internal relative humidity is demonstrated for the isothermal case.

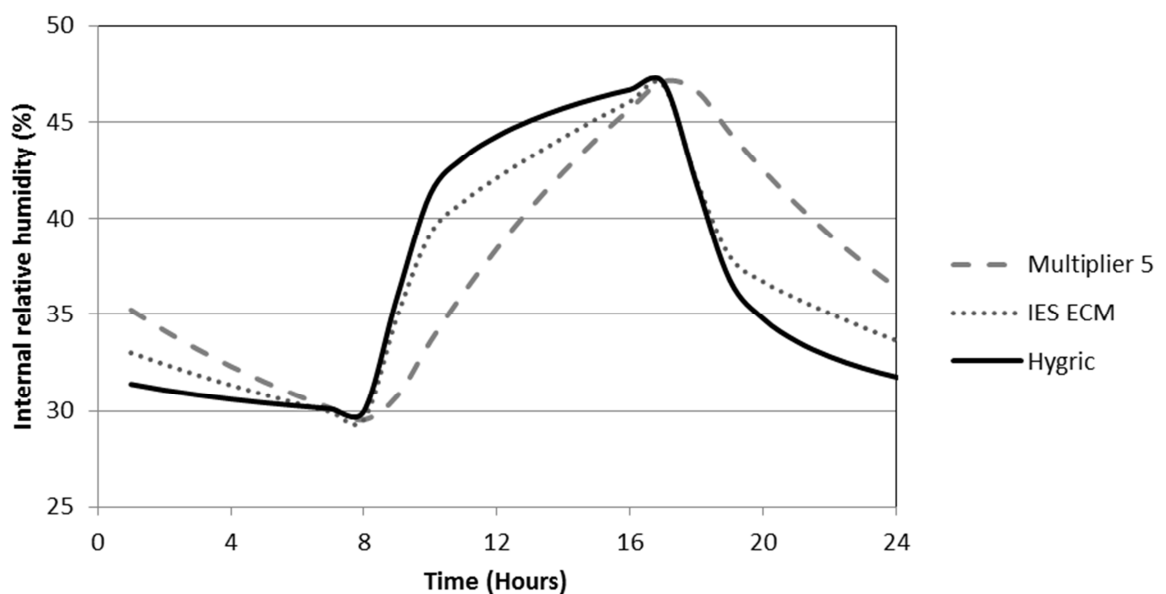


Figure 11 Comparison of the IES ECM moisture buffering performance with the Energyplus Multiplier 5 model and the full EnergyPlus Hygric model.

Combining the moisture capacitance of the normal zone air and the extra moisture admittance from the IES ECM produces second order humidity behaviour. This can fit the full hygric model more closely than the simple effective capacitance model (Multiplier 5). Some adjustments would have to be made to ensure that temperature capacitance of the buffer zone does not affect the results when a realistic weather file is used instead of the isothermal case. HVAC heating and cooling equipment could be used to correct for this temperature capacitance. Another option would be to have a deeper internal integration of this model in the IES software, with the separation of the moisture buffering calculation from the air enthalpy calculation. Such a separation is how the EnergyPlus effective capacity model is implemented. The results in Figure 11 illustrate the potential of having both a capacitance and a resistance component to modelling moisture buffering. The IES ECM results are closer to the full hygric simulation result than both the Energyplus effective capacity model and clearly better than the closed result shown in Figure 9. This closed result is the same as IES's default behaviour.

The parameters that control the resistance and capacitance of the model need to be sized and a method would need to be developed to do this. It is proposed that a similar approach to the thermal admittance method described in CIBSE Guide A [22] could be used. This draws on the thermal behaviour of buildings described by electrical analogy [24]. For internal moisture buffering, the moisture admittance  $Y_m$  would be given by:

$$Y_m = \frac{1}{R_m + iX_m}$$

Where  $R_m$  is the resistance to moisture flow and  $X_m$  is the reactance to moisture flow. For the IES effective capacity model  $R_m$  would be inversely proportional to the circulating fan speed and  $X_m$  would be proportional to the size of the capacity zone. A method could be developed to determine these components of moisture admittance from dynamic moisture buffering experiments. In the moisture buffer experiment described in ISO 24353 [19] the oscillating air humidity could be represented by a square wave. Characterising the buffering behaviour from one such experiment would significantly reduce the requirements for extensive material testing which are needed for full hygric simulation and were outlined in Section 2. To continue the electrical analogy, the exposed areas of buffering construction materials or furniture could be added as if they were electrical components to determine the zone moisture admittance due to the hygric materials.

## 6. Conclusions

In this paper a complete set of hygrothermal material properties have been presented for hemp-lime. These material data are then used for simulation. The Wufi Pro results showed a very close fit in terms of peak moisture buffer value but for the EnergyPlus HAMT model a relatively large difference of 18% was observed. The underlying calculation methodologies of both these software tools are based on the same fundamentals [7]. Accordingly, the resolution of the discretization was investigated and shown to be a possible reason for the 18% difference as increasing the coarseness of the Wufi Pro discretization also increased the peak result. It is recommended that

increasing resolution should be part of attempts to improve EnergyPlus HAMT model accuracy.

EnergyPlus was used for whole building performance and modelling identified that internal relative humidity was highly sensitive to the application of hygric simulation. The use of full hygrothermal simulation was shown to have relatively little influence on the peak loads and yearly energy demand of the BESTEST building. Overheating for the free-running simulation was shown to reduce by 0.6% with the use of full hygric simulation. For the BESTEST case investigated internal relative humidity was the most sensitive parameter to hygric materials and so effective capacitance methods were investigated which could reduce computational resources and material testing requirements. Capacitance models do not calculate moisture distributions in the construction materials so full hygrothermal simulations will still be required where such information is desired.

The effective capacitance model was explored as a simplified method for determining the internal relative humidity buffering of hemp-lime. A capacitance multiplier of 5 was found to give a good approximation of peak humidity buffering for the hemp-lime BESTEST building. However, without resistance to accessing this buffering capacity, the performance did not follow the same dynamic response to bursts of humidity. Implementing a capacitance-resistance model in IES Apache-HVAC produced second order relative humidity buffering behaviour, which produced a better fit to the full hygric simulation. It is suggested that adopting a moisture admittance approach could be useful to determine the resistance and capacitance parameters from moisture buffering component level testing. Such an approach could reduce the requirements for materials testing to calculate whole building moisture buffering.

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